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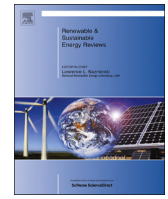

# Overview of subsynchronous resonance analysis and control in wind turbines

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Considering the rapid growth of wind turbines applications in power systems, the dynamic behavior of wind turbines, especially the subsynchronous resonance (SSR) is of interest to researchers. This paper presents an overview of subsynchronous resonance issues in wind turbines including, analysis methods, modeling, the impact of control parameters, and proposed mitigation methods. Much of this study is focused on variable speed wind turbines.



**Contents**



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## 1. Introduction

Power systems all around the world are facing with reduction in fossil fuel resources, environmental issues and energy crises [1]. Thus, new approaches for generating low-carbon, renewable energy sources such as natural gas, biogas, wind power, solar photovoltaic, fuel cells, micro turbines, etc. are necessary [2–4].

The wind energy has the fastest growth among the various resources [5,6] and has produced thousands of megawatts of electric power energy in different countries [7–11]. Today, new wind turbines, with a capacity greater than 3500 kW, are in operation [12] and wind farms are considered as an important resource for future power systems [13].

There are some requirements for the connection of large wind farms to the gird [14]. One of the major issues and challenges is the turbine control and troubleshooting during the connection and fault conditions [15,16]. Therefore, the dynamics of wind turbines especially when lots of wind turbines are connected to the grid as a wind farm should be studied [17,18].

Upgrading the transmission infrastructure through construction of new transmission lines is required by increasing in the capacity of installed wind farms [19]. An effective alternative for increasing the transmission line capacity is series compensation which is considered for the integration of large wind farms [20–22]. However, this also leads to the phenomenon of the subsynchronous resonance (SSR), which stimulates the generator torsional modes when the modal frequencies align with the system resonance created by the series compensation [23–25]. Recent events have shown that if the wind turbine generators are connected to the series compensated radial transmission lines, SSR occurs when the compensation level increases [26,27]. Therefore some mitigation measures should be taken.

Nowadays, Double-Fed Induction Generators (DFIG) are used in a large number of wind farms in various countries. However, the instability and control issues in the power system may limit their applications in the future [28,29]. Therefore, this study focuses mainly on wind farms composed of variable speed wind turbines (especially DFIG), an integrated system of DIFG with back-to-back power electronic converters. These converters have the capability of maximum power point tracking (MPPT), active and reactive power control, frequency control [30–34], the unbalanced network conditions compensation [35] and dynamic stability improvement [36,37].

The resonance frequencies of DFIG highly dependent on both rotor-side and grid-side converters control parameters. Flexible AC Transmission System (FACTS) devices have been also considered as effective controllers to improve the dynamic stability [26,27,38–46].

The objectives of this paper are (1) review of sub-synchronous resonance considering different wind turbine configurations, (2) analysis of subsynchronous resonance phenomenon for large wind farms connected to the grid through series compensated lines, and (3) review of control methods to mitigate SSR.

The paper has been organized as follows. Section 2 describes a brief review of the problem that is the SSR and analysis of this phenomenon in power systems. In Section 3, the impact of SSR on different wind turbines, i.e., constant-speed, with full-power converter, and DFIG turbines, is presented. Section 4 investigates the modeling issues and SSR analysis of DFIG. Section 5 studies the different control methods to mitigate SSR. Conclusions and recommendations for future works are given in Section 6.

## 2. Sub-synchronous resonance in power Systems

The capacitive series compensation of long transmission lines is one of the most effective and available methods to increase the transmission capacity and improve the stability of the system [49]. In addition to the advantages of series capacitor, there is another problem, which is, by installing a series capacitor in a transmission line, the circuit of transmission line would become RLC that has both natural and resonance frequency. Intervene of each of these torsional oscillation frequencies with this resonance frequency may cause the sub-synchronous resonance.

The sub-synchronous resonance can be defined as follows:

Assuming that due to some reasons, one of torsional modes of the rotor be exited (for example, the $f_m$ Hz frequency, i.e. a $f_m$ Hz frequency be over the synchronous frequency of $f_s=60$ Hz); then two frequencies of $f_s+f_m$ and $f_s-f_m$ will replace with the $f_s=60$. If one of these two frequencies become close to the resonance frequency of transmission line, the current amplitude will be increased, hence, based on the $T_e=v_d i_d+v_q i_q$ formula, the electric torque will be increased in this frequency. Increase in the electric torque would lead to amplification of torsional oscillation amplitude on the rotor, and due to the interaction between the electric and mechanical system the torque domain will increase more and more, so that reach to the unbearable amplitude for the rotor. The reason that such phenomenon is called SSR is that, this phenomenon would usually occurs for $f_s-f_m$. This phenomenon is related to a resonance situation that led to the energy exchange between the generator and transmission line [50], which may lead to serious damages in generator units. The SSR was diagnosed in Mohave generation station in 1970 for the first time [51]. In [52,53], it has been studied in series compensated systems with synchronous generators.

### 2.1. Classification

Based on the IEEE Standard, SubSynchronous Resonance is classified into three main groups [50,52]:

- Group A: Induction Generator Effect (IGE)
- Group B: Torsional Interaction Effect (TI)
- Group C: Transient Torque (also called Torque Amplification (TA)).

#### 2.1.1. Induction generator effect (IGE)

IGE is an absolute electrical phenomenon in frequencies close to the nominal frequency of the grid. IGE is usually caused by self-excitation of electrical systems and is not involved with the mechanical systems of generation units. The rotor resistance, seen from the rotor side, is against the negative sub-synchronous currents. The grid provides a positive resistance for these currents. If the size of the negative resistance of the generator be greater than the grid resistance, the continuous sub-synchronous currents will be induced. In fact, IGE may occur in all types of power plants, even in hydro generator units [53,54].

#### 2.1.2. Torsional interaction effect (TI)

TI is an unstable state that results in an energy exchange between the electrical power system and generator shaft. TI, especially occurs when the inducted torque is electrically close to the one of natural frequencies in the generator. When this phenomenon occurs the rotor oscillations occur as well, and the motion will induce the armature voltage components in both sub-synchronous frequencies (the system frequency and the natural frequency of the generator shaft). If the sub-synchronous torque be equal to or more than the intrinsic mechanical damping, the system will be self-induced. This type of SSR does not happen in hydroelectric power plants, because the inertia of generator is much higher than the turbine generator inertia. Therefore, oscillations will not be happened in in the power system. Instead, the SSR due to TI can occur in thermal power plants, because the

inertia of generator is equal to the turbine generator inertia [53,54].

*2.1.3. Torque amplification (TA)*

TA is a phenomenon that occurs due to the disturbances of the system (like short circuit failures). Any disturbance may cause sudden changes in the current, which tends to make a fluctuation. In non-series compensated transmission lines, these disturbances will result in a dc offset, which reduces transient and sub-transient time constants of the generator. Instead, in a series compensated line, oscillations with frequencies corresponding to the grid resonant frequency are created. If the frequency of oscillations be close or coincide the one of natural frequencies of the generator shaft, larger torques will occur. The occurrence of SSR due to TA can cause severe torsional mechanical oscillations in the shaft system of thermal power plants. Mathematical analysis of the torque amplification effect is complex and can be approximated using simulation programs.

Among above-mentioned groups, the first two can be considered as stable SSR with small disturbance situations. But, the third group has a non-linear nature and cannot be considered as a small disturbance [53,54].

Analysis of self excitation or shaft transient torque, which is the result of disturbances in electrical systems, requires mathematical modeling of mechanical torsional system. To represent this system fully, we need to resolve the elastic behavior of total turbine-generator. One of the proposed mechanical methods, is the spring-mass model, Fig. 1, which provides the conditions to calculate the rotor motion by torques are applied to the individual masses as inputs [50]. In fact, due to the flexibility of the rotor, in some cases the mechanical torque is applied to one side of the rotor and the electrical torque to the other side and, therefore, two sides of the rotor will have different angles. The difference between the relative angular velocity of two sides is called the torsional oscillations (oscillations of one part of the rotor to the other parts). The torsional oscillations are usually considered for steam turbines, for rotor length in this type of turbines is much, and the probability of a different angle of different parts is more than other turbines with low length. One of the methods used to protect against mechanical stress resulting from the SSR is use of Torsional Motion Relay. This relay detects the over-mechanical stresses in the shaft of turbine-generator and operates to disconnect the machine from the network. The relay is primarily applied to protect against the torsional interaction effect, and evidently is slow to protect against transient SSR [106].

In fact all types of SSR phenomenon can cause stresses on the shaft system of the power plants, and if the system operators do not act fast, both mechanical and electrical damage can occur due to the low power available and large economic losses.

Fatigue is a process of continuous and permanent changes in the structure of the material due to conditions such as pressure and stress on one or more points, and may cause injury or full fracture after a certain number of oscillations. Transient disturbances reduce the life time of turbine-generator shafts. The effect of loss of rotor life is a cumulative effect. This means that if one time a fifty percent, then thirty percent and finally twenty percent of the rotor life reduces, the rotor will break. This matter is very important, especially in cases where there is a sub-synchronous resonance [50].

*2.2. Methods of analysis*

There is several methods to analyze the SSR. Amongst, the frequency scanning [55,56], eigenvalue analysis [57,59], and electromagnetic transient analysis [60] are the most used methods. The frequency scanning and the analysis of eigenvalues are based on linear models of machines and power system and are preferable for SSR studies caused by induction generator and torsional interaction effect. Also, due to the complexity of equations of the system in modeling, the electromagnetic transient analysis is preferable to study the circumstances that may result in transient torque.

## 3. Risk of SSR in wind turbines

The wind turbines are generally divided into two categories:

- fixed speed wind turbines, and
- variable speed wind turbines.

The difference between these two types is not just based in terms of frequency dynamic behavior, but also such difference can be observed due to SSR phenomenon.

*3.1. SSR in fixed speed wind turbines*

The fixed speed wind turbines typically have induction generators (IG), which are directly connected to the electric grid, as shown in Fig. 2. This type of fixed speed wind turbine consists of a capacitor bank to compensate the reactive power of the induction

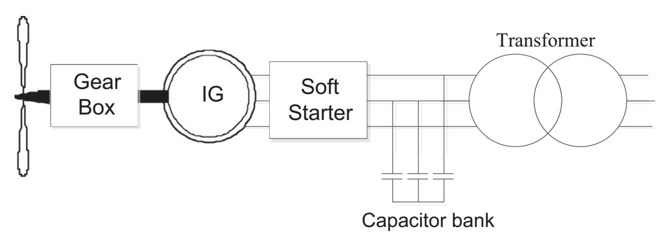


**Fig. 2.** Fixed speed wind turbine with conventional induction generator.

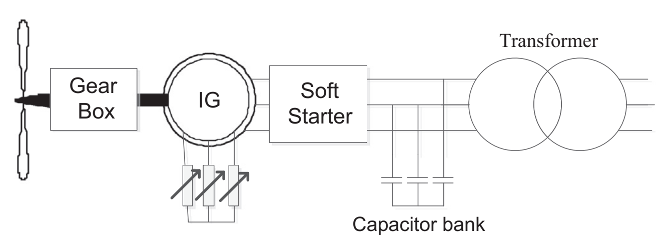


**Fig. 3.** Fixed speed wind turbine with variable slip induction generator.

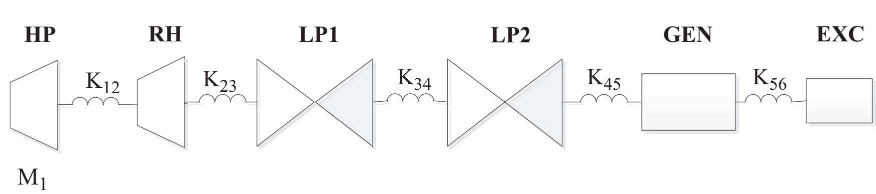


**Fig. 1.** Torsional system [50].

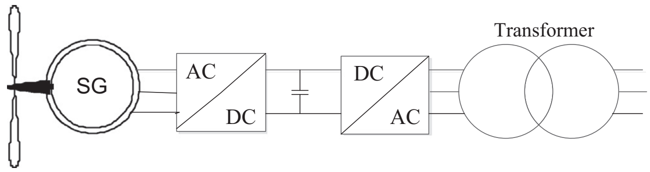


**Fig. 4.** Variable speed wind turbine with full-power converter.

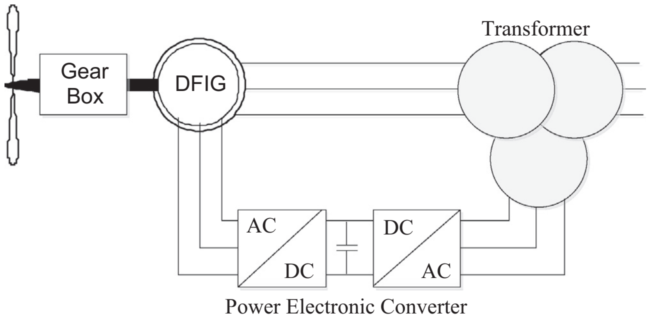


**Fig. 5.** Variable speed wind turbines with DFIG.

generator, and a soft starter to connect the generator to the grid. Another type of fixed speed wind turbines with variable slip is shown in Fig. 3. In this system, the IG has a wound rotor connected to resistances. Fixed speed wind turbines, connected to series compensated lines may be faced with SSR conditions. The main reason for the occurrence of this phenomenon is related to the IGE in system characteristics. In some special circumstances, SSR may also occur due to TI [26,27,61]. Typically, this type of wind turbines was used in the very basic applications, but nowadays the variable speed wind turbines have higher flexibility and efficiency. Therefore, recent researches about SSR focus on variable speed wind turbines.

### 3.2. SSR in full-power converter wind turbines

One of the reasons to use variable speed wind turbines is their facilities to reduce the tension on the mechanical structure and control the active and reactive power [62]. The full-power converter wind turbine is one of these turbines, as shown in Fig. 4. In this type of turbine, the back-to-back converter provides an isolation between the grid and the turbine. Since the convertor is operating in a linear range, if a variation occurs on the grid-side converter, it will not reflected to the wind turbine. Therefore, these turbines are safe against the SSR phenomenon [63]. There is a similar view for wind turbines connected to power systems through the HVDC links. When the grid-side converter of the HVDC link operates as a rectifier, there is a risk of SSR occurrence, and when the grid-side converter operates as an inverter, there will be no risk of SSR occurrence, due to positive damping on sub-synchronous frequencies [64]. In [65–68], modeling, control, and coordination between HVDC link and DFIG have been studied. A mathematical approach has been presented for HVDC systems in [69,64] in order to facilitate the sensitivity analysis of the system.

### 3.3. SSR in DFIG wind turbines

The most versatile type of wind turbines are doubly-fed induction generators [70–72]. A type of variable speed wind turbines with doubly-fed induction generators (DFIG) is shown in Fig. 5.

The back-to-back AC/DC/AC converter, located between the rotor winding and the grid, consists of two voltage-sourced converters, a rotor-side converter (RSC) and a grid-side converter (GSC).

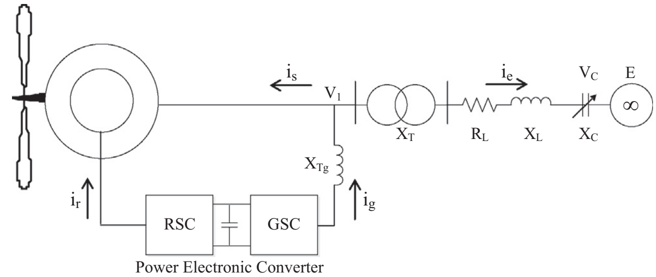


**Fig. 6.** Schematic diagram of wind turbine equipped with DIFG for SSR studies.

**Table 1**
Torsional modes for various stiffness constant. wind speed at 9 m/s and compensation level at 75% [59].

| $K_{tg}$ | Eigenvalue | $f_{TI}$ (Hz) |
|---|---|---|
| 0.15 | −2.69 ± j31.74 | 5.05 |
| 1 | −2.24 ± j33.70 | 5.36 |
| 2 | −1.81 ± j36.26 | 5.77 |
| 3 | −1.48 ± j38.93 | 6.20 |
| 10 | −0.74 ± j56.19 | 8.94 |
| 50 | −0.52 ± j115.28 | 18.35 |
| 100 | −0.35 ± j162.45 | 25.85 |
| 150 | −0.16 ± j193.79 | 30.84 |
| 200 | −0.49 ± j225.42 | 35.87 |
| 250 | −0.05 ± j252.1 | 40.12 |

The rotor-side converter is dealt with the rotor power which is a part of the nominal power of the generator (approximately 30%); this means that the losses in the converters can be reduced compared to the case, where the full power passes through convertors. In addition, the cost of the converters is lower [73–75]. In short, it can be said that the main advantage of this type of wind turbine is that their converters can keep the frequency and the output voltage amplitude constant, because they operate synchronous with the grid all the time. But in the fixed speed wind turbines, in case of any changes in the wind speed, the mechanical parts are under stress and so the torque of the rotor will increase and consequently, the output power of the generator will suddenly change; and this may cause instability in the AC grid. Another advantages of DFIG are the possibility of the power factor control, generating power at low speed winds, and the optimization of the generated power as a higher function of the nominal power in the wind turbine generator [75–77].

Several years ago, power systems dynamic experts believed that the DFIG is safe against the SSR, same as full-power converter. This is mainly due to the ability of control systems of DFIG for torque control. However, in October 2009, an incident in the Zorillo Gulf wind farm (Texas) occurred that based on researches, this incident was identified as SSR phenomenon [79,78].

## 4. Modeling of DFIG for SSR analysis

The resonance frequency in series compensated grid is $f_n = f_0\sqrt{X_C/X_L}$, where $f_0$ the is synchronous frequency and $f_n$ is the natural resonance frequency in Hz. At sub-synchronous frequency, $s_1$, the slip is expressed as follows:

$$s_1 = \frac{f_n - f_m}{f_n} \tag{1}$$

where, $f_m$ is the electric frequency that corresponds to the speed of the rotating field. Since $f_n$ is less than $f_m$, then $s_1$ is negative.

Wind farms equipped with DFIG have been modeled for SSR studies based on the IEEE first experimental model [80].

According to Fig. 6, this model includes a set of DFIGs in the wind farm, which is connected to a series compensated line. In [81–86], the operation of a set of wind turbines has been modeled by an equivalent lumped machine. These studies have shown that a single-machine model is sufficient for the most of studies.

For modeling the DFIG wind farms connected to series compensated lines, aerodynamic wind turbine model [87], series compensated grid model [88], induction generator model [89], DC Link model, and torsional dynamic model [90] should be used for SSR analysis. The overall system model, ignoring the converter controllers (14th order), can be described as follows:

$$\dot{X} = f(X, U) \tag{2}$$

where, we have

$$X = [X_n^T,\ X_g^T,\ v_{dc},\ X_t^T] \tag{3}$$

The modeling and stability analysis of a DIFG wind turbine connected to series compensated transmission lines have been presented in [91]. In the paper, the dynamic model of the phase-locked loop (PLL), power electronic converter controllers and wind turbine has been discussed, and it has been shown that the control parameters of the rotor-side current have the most important influence on the stability of the power system. The authors did not consider any difference between two SSR phenomena, and did not present the relationship between turbine parameters and torsional oscillation modes. The model in this study has been simulated by PSCAD/EMTDC software. Other studies like [92] have used this software, but also others have used ATP/EMTP [93] for SSR simulations in the time domain. In [94], the DFIG model for SSR has been studied by in Matlab/Simulink software.

To analyze SSR phenomenon, the eigen properties of the system can be studied. For a complex pair of system eigenvalues $(\lambda = \sigma \pm j\omega)$ can be said to be a system mode with an oscillation frequency $f = (\omega)/(2\pi)$. Damping ratio is defined as $D = (-\sigma)/(\sqrt{\sigma^2 + \omega^2})$. If the real part is positive, the system will be unstable with a negative damping.

It is shown that the oscillatory mode of the torsional dynamics highly depends on the stiffness of the shaft ($K_{tg}$). The shaft of the wind turbines has a little stiffness constants [95] in comparison with steam and water turbines and diesel generators. In [59], an analysis is performed to identify the parametric conditions of IGE and detection of torsional interaction (TI). The dependence of the torsional mode and its corresponding frequency $f_{TI}$ on shaft stiffness ($K_{tg}$) is tabulated in Table 1 below using eigenvalue analysis. From Table 1, it is found that at normal range of shaft stiffness ($K_{tg}$), the frequency of the torsional mode is less than 10 Hz. In this study, using eigenvalues analysis and time domain simulations, it is demonstrated that torsional interactions may occur just in unusually high shaft stiffness, which is unlikely for the wind turbines. Therefore, in the variable speed-DFIG based wind farms, IGE is the major cause of SSR instability instead of TI. Unlike fixed speed systems, the damping of the grid mode, may be improved by increasing the wind speed, and increasing the compensation level (i.e., $f_n$ increases but $f_0 - f_n$ decreases) will reduce the damping of the system. The damping of the network resonant mode at various compensation levels for different wind speeds are shown in Fig. 7 using eigenvalue analysis. In contrast, the damping of the torsional mode is not sensitive to changes in wind speed and the compensation level has more influence on the TI than the wind speed. The variations of network and torsional modes with wind speeds, at fixed compensation levels are listed in Table 2 [57,59].

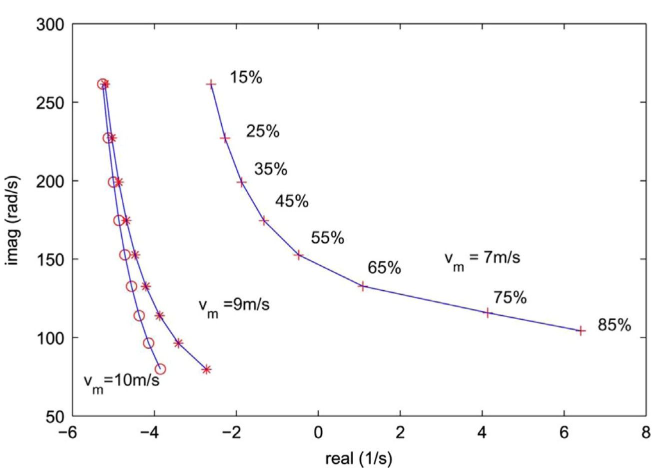


**Fig. 7.** Network resonance mode at various compensation level for different wind speed. frequency of mode is ($f_0$-$f_n$) [59].

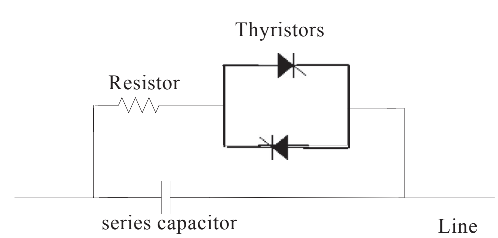


**Fig. 8.** Diagram of linear NGH damper.

**Table 2**
Torsional mode and network mode at various wind speeds [59].

| % Comp. | Wind speed | Torsional mode | | | Network mode | | |
|---|---|---|---|---|---|---|---|
| | | $\sigma \pm j\omega$ | $f_{TI}$ (Hz) | $\xi$ | $\sigma \pm j\omega$ | $f_s$-$f_n$ | $\xi$ |
| 75% | 7 m/s | 11.2 ± j119.6 | 19 | −9.36% | −11 ± j115.3 | 18.4 | 9.5% |
| | 8 m/s | 6.5 ± j115.2 | 18.3 | −5.62% | −9.2 ± j114.2 | 18.2 | 8.58% |
| | 9 m/s | 4.4 ± j114.5 | 18.2 | −3.84% | −8.2 ± j114.2 | 18.2 | 7.7% |
| | 10 m/s | 3.2 ± j114.6 | 18.2 | −2.8% | −8.2 ± j114.2 | 18.2 | 7.3% |
| 25% | 7 m/s | −0.69 ± j118 | 18.8 | 0.58% | −11.2 ± j226.8 | 36 | 1% |
| | 8 m/s | −0.36 ± j115.2 | 18.3 | 0.31% | −11.2 ± 227 | 36 | 2.2% |
| | 9 m/s | −0.49 ± j114.6 | 18.3 | 0.43% | −11.2 ± j227 | 36 | 2.2% |
| | 10 m/s | −0.73 ± j114.6 | 18.3 | 0.64% | −11.2 ± j227 | 36 | 2.3% |

## 5. Control and mitigation of SSR in wind farms

In recent researches, measures have been taken to prevent or reduce the risk of SSR in wind farms; here is a summary as follows:

### 5.1. Impact on power system

Sub-synchronous resonance may occur in series compensated power system under certain conditions. Choosing an appropriate level of series compensation, to ensure that the grid resonance frequency not being so close to system natural frequencies, is effective, as well as choosing complementary of one of natural frequencies of the shaft generator to prevent this problem. This solution is not feasible, since the amount of the grid impedance, thus its resonance frequency, varies depending on the operating conditions of the power system. The application of parallel compensation instead of series compensation is possible as well. But the parallel capacitors may cause super-synchronous resonances [25]. Therefore, when there is the possibility of using a combination of series and parallel compensation, its application can be a good solution.

### 5.2. Impact of turbine-generator parameters

In fact, shaft natural frequencies are within a narrow band and cannot change significantly. Therefore this would have not much influence on the SSR phenomenon due to unknown grid resonance frequency. The application of pole-face damping windings can reduce the negative resistance of the generator seen from the terminals of the machine [25]. However, installing such windings on older machines is impossible and impractical. Moreover, this solution is effective only for SSR due to IGE, and has no effect on SSR caused by TI and TA.

### 5.3. Using auxiliary Devices

One of the most common methods, used to reduce the SSR, is installing auxiliary devices in the power system. Researches about dealing with SSR are mainly considering such a solution. A brief explanation of the main solutions is presented as follows:

#### 5.3.1. NGH-damping scheme

NGH (N.G. Hingorani) damping scheme, as shown in Fig. 8, consists of thyristor, series capacitor and a resistance [96,97].

This solution is effective in reducing the SSR caused by TI and TA. However, some studies the shown that torsional modes that are not in resonance with the electrical system, might be somehow undamped [25].

#### 5.3.2. Blocking filter

As shown in Fig. 9, a simple method to reduce SSR is the installation of blocking filters in series with the winding of the step-up transformer of the generator. Typically, the filter is inserted on either the neutral point, at the end of the high voltage side of the transformer. The filter also can be installed on the high voltage phase side of the step-up transformer. This type of filter is a three-phase blocking filter that is used to block the components of a line current with frequencies. Each of the blocking filters is tuned for one single natural frequency of the turbine-generator shaft system. The filter is tuned to contribute positive resistance at frequencies which coincide with the complement of the torsional natural frequencies. In addition, combining the filter impedance characteristics introduces parallel resonances at the rotor complementary frequencies. This causes the system series resonance points to shift to frequencies that cannot damage the machine. The phase blocking filter is effective to reduce both SSRs due to TI and TA [98,106].

One disadvantage of this solution is that the filtering depends upon the system frequency and changes in the amount of filter components due to temperature and life duration reduce the effectiveness of filters. To implement so in three-phase systems, it requires larger filters. Therefore, this solution cannot be used for SSR on wind farms.

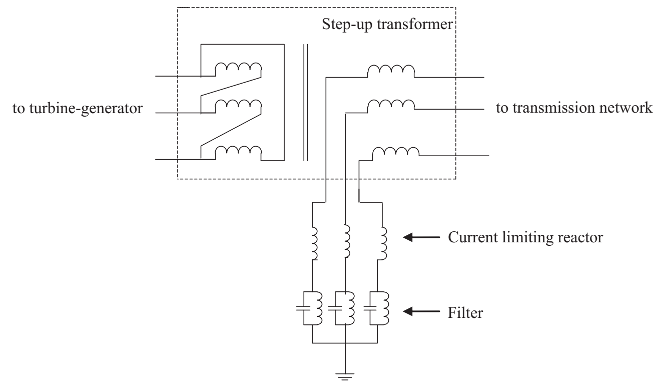


**Fig. 9.** Three-phase transformer with blocking filters.

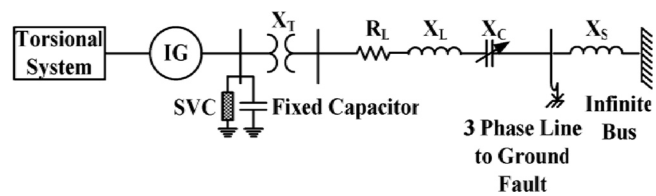


**Fig. 10.** Wind turbine with SVC [42].

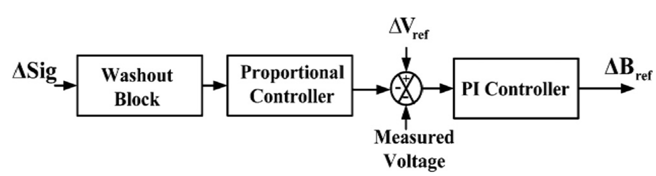


**Fig. 11.** Damping controller of SVC for SSR [26].

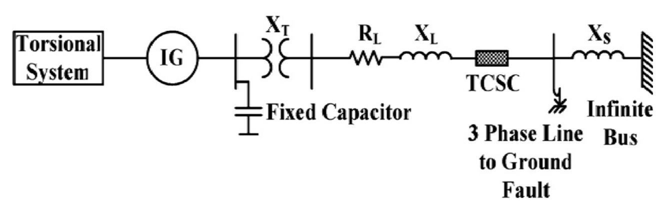


**Fig. 12.** Wind turbine with TCSC [45].

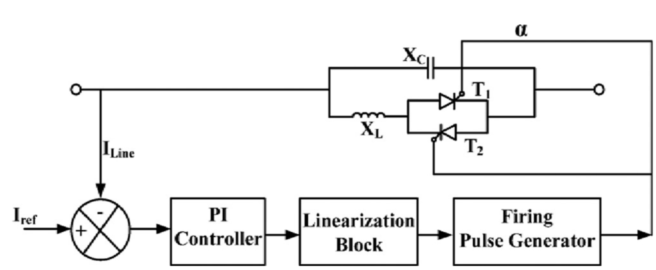


**Fig. 13.** TCSC constant current controller [26].

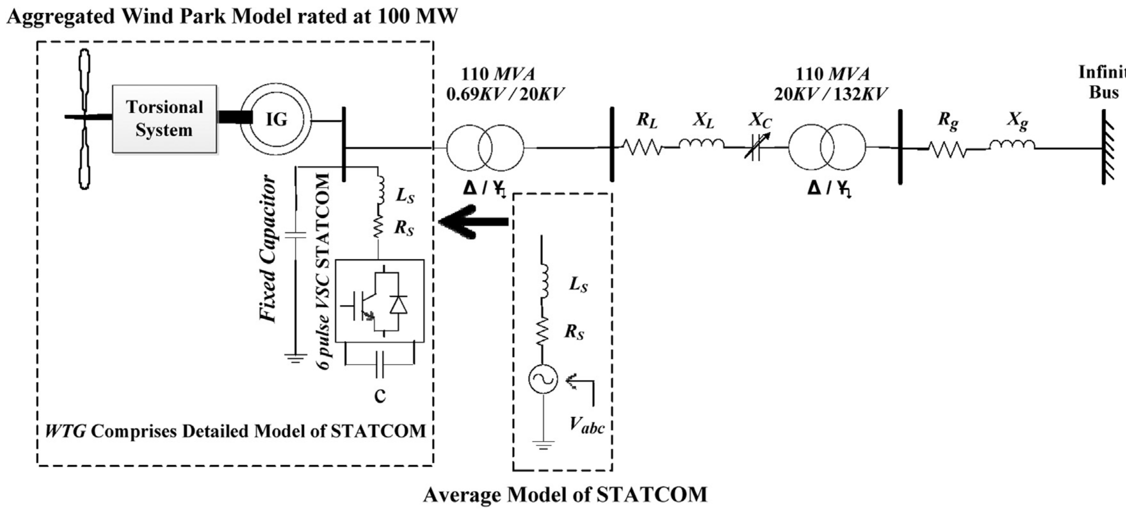


**Fig. 14.** Wind farm with STATCOM [27].

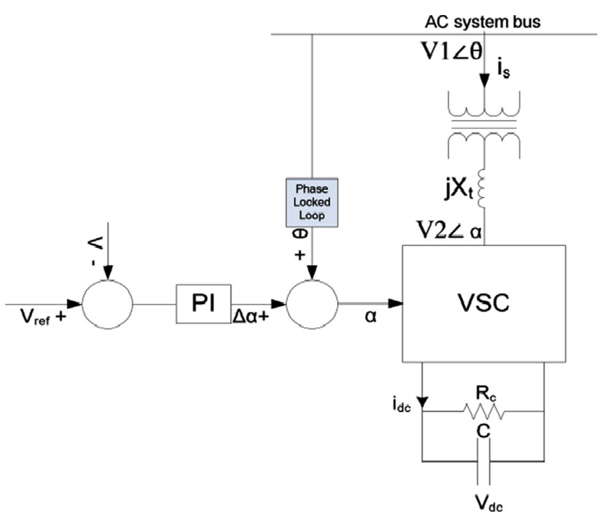


**Fig. 15.** STATCOM Model [46].

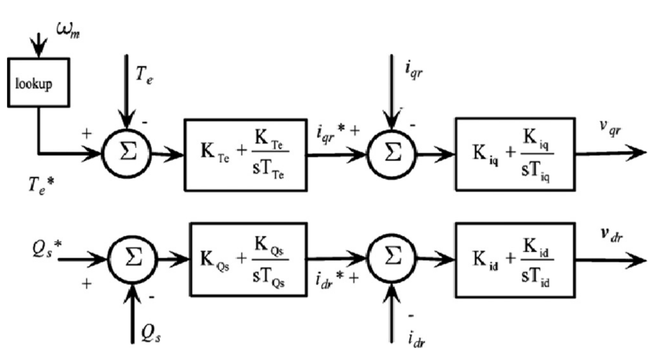


**Fig. 16.** RSC control loops.

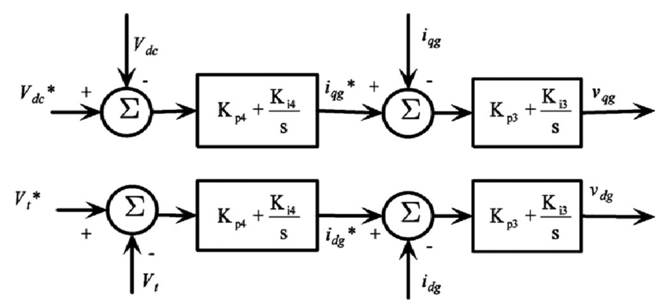

**Fig. 17.** GSC control loops.

### 5.3.3. FACTS devices

Flexible AC Transmission Systems (FACTS) controllers are considered as one of the most effective solutions for the SSR in transmission networks. Many researches have proposed the application of FACTS devices in transmission lines to reduce SSR in wind farms [48,26,27,42,46].

FACTS devices can be connected in series or parallel. Both connections can dynamically improve the SSR phenomenon. Devices, connected in series, are usually more effective for damping oscillations than parallel structure [25,97]. The reason is the direct relationship between voltage and flux.

In recent researches, the reduction of SSR in wind farms connected to series compensated lines using self-excited induction generators, has been studied [26,42,45]. In these studies, using simulation results by EMTDC/PSCAD software in two separate modes, the capability of Thyristor Controlled Series Capacitor (TCSC) and Static Var Compensator (SVC) to reduce the SSR has been presented. In the first case, SVC, equipped with a voltage regulator in induction generator terminal and a fixed shunt capacitor have been used to support the reactive power and damp the SSR (as shown in Figs. 10 and 11). In the second case, TCSC shown in Fig. 12 is used. As shown in Fig. 13, it has a closed-loop flow controller for SSR damping. In both cases, the generator speed has been used as an auxiliary signal for controller, and it has been shown that

- Both cases are effective for damping SSR but TCSC has a better performance than the SVC.
- Wind farms with higher output power have less damping [26,42,45].

Also, STATCOM can significantly reduce the SSR [27,48]. In [27], the first experimental model of IEEE has been used for the study of SSR. In this study, as shown in Fig. 14, the induction generator effect (IGE) along with the torsional interaction (TI), has been studied. In the paper, an auxiliary controller has been used for STATCOM to damp the SSR. The damping torque analysis and rotor speed as input signal have been used for the controller. Therefore, using a damping torque for torsional mode frequencies and auxiliary control by STATCOM, the SSR has been reduced and the stability of the power system has been achieved.

In [46], using STATCOM shown in Fig. 15 and adjusting the parameters of PI controller, the reactive power exchange between the AC system and STATCOM has been controlled for damping the torsional oscillations and improving transient stability of wind farms.

### 5.4. Controlling Converters of DFIG

As mentioned in the previous section, FACTS devices can reduce SSR and stabilize the system, but installation of such equipment is expensive for the owner of the wind farm. Using such devices just for SSR damping may not be so cost effective. The most of wind turbines in different countries, including the United States, are DFIG type [47]. Another method of reducing the oscillations of the power system and inter-area oscillations is the control of DFIG converters in wind farms [37,48,99–101].

DFIG has two voltage source converters including rotor-side and grid-side converters (RSC and GSC, respectively). Control loops of these converters to reduce SSR have been presented in [102] and shown in Figs. 16 and 17. The RSC control loop gains a negative impact on the SSR network mode. It is, therefore, not suitable to explore SSR mitigation through RSCs [59,91]; instead, the GSC can have a considerable effect on reducing oscillations [56,58]. In this converter the loop of the $q$-axis is to adjust the active power and the loop of the $d$-axis is to set the reactive power. The topology of the grid-side convertor in DIFG for the exchange of the active and reactive powers is the same as STATCOM. Reducing SSR by controlling GSC needs a proper control signal that has been studied as follows:

### 5.5. Control signal selection

In [27,26,58], the rotor speed is used for the control and reduction of SSR in wind farms; (the rotor speed reflects mainly the torsional mode), but to decrease both sub-synchronous and super-synchronous modes other signal should be used.

As mentioned in the previous section, the main reason for SSR is the resonant mode of the grid, and so proper measurement of the mode shall be selected as control signals. The analysis of residues has a major role in selecting the control signal and the residues corresponding eigenvalues can be calculated according to the following equations. The state space model and the transfer function of a single-input single-output device are expressed as follows:

$$\dot{X} = AX + BU \tag{4}$$

$$Y = CX \tag{5}$$

$$\frac{Y(s)}{U(s)} = G(s) = \sum_{i=1,2,\ldots,n} \frac{R_i}{s-\lambda_i} \tag{6}$$

$$R_i = CV_iW_iB \tag{7}$$

where, $X$ is the vector of state variables, $A$ is the system matrix, $B$ is the input matrix, $C$ is Output matrix, $Y(s)$ is the machine output, $U(s)$ is the machine input, $R_i$ is residues corresponding $\lambda_i$, $V_i$ is the $i$th column of the matrix $V$, $\lambda_i$ is the $i$th root of the system, and $W_i$ is the $i$th column of the matrix $W$. $R_i$ shows the direction and speed of the system root of closed loop. The larger the size of $R_i$, the greater the effect of the feedback control [103].

Both the line current ($I_{line}$) and series capacitor voltage ($V_c$) well reflect the SSR oscillations. If the line current is selected as the control signal, the system will be unstable. But the capacitor voltage is recognized as a proper signal to reduce the SSR in wind farms to raise damping for SSR and super- synchronous mode by using auxiliary damping controller for modulation of the terminal voltage or DC link voltage in GSC control loops. The capacitor voltage is a remote signal; but the signal can be estimated by local measurements, according to the Eq. (8), and using the control algorithm shown in Fig. 18.

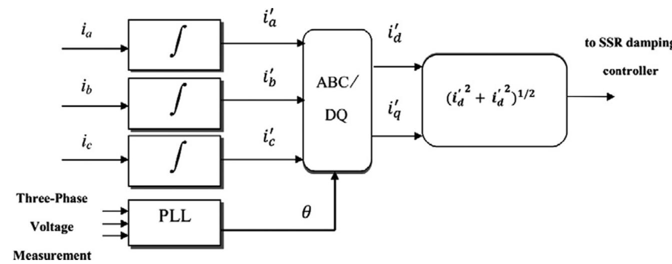


Fig. 18. Estimation of capacitor voltage ($V_C$) via local measurements of currents [56].

$$C\frac{dv_{c,p}}{dt} = i_p, \quad p = a, b, c \tag{8}$$

The reason for the considerable difference of $V_C$ and $I_{line}$ signals in different control characteristics of sub-synchronous and super-synchronous frequencies is $-180°$ phase difference between these two modes [56]. To understand the relationship between two phasors, the dynamic phasor concept can be used [104]. The capacitor voltage as a proper control signal is also effective in damping inter-area oscillations, in addition to damping of sub-synchronous and super-synchronous oscillations [105].

## 6. Conclusions

The subsynchronous resonance in wind turbines including, analysis methods, modeling, the impact of control parameters, and mitigation methods have been reviewed in this paper.

The following conclusions can be drawn:

- Frequency analysis, electromagnetic transient analysis, and eigenvalues analysis have been mainly used for SSR analysis. Since the SSR phenomena is caused by Induction generators in DFIG-based wind farms, the frequency and eigenvalue analysis are the best options for SSR and torsional studies.
- Fixed speed wind turbines, connected to a series compensated transmission line, may experience SSR. The variable speed turbine equipped with full size converters are not experiencing SSR due to the dc-link of back-to-back converter which isolates the machine form the electrical power transmission line. There are different scenarios for variable speed DFIG wind turbines regarding SSR. The first event, which has been identified as SSR, is related to this type of wind turbines.
- Unlike fixed speed turbines, the network damping improves when the wind speed increases in DFIG based wind farms. However, the system damping decreases with increasing compensation level. Torsional interactions occur only for high values of the shaft stiffness, which is unlikely for wind turbines. Therefore the damping of the torsional mode is insensitive to wind speed variations.
- An optimized controller for mitigating the SSR can be designed using the integration of series and parallel compensation devices, auxiliary controllers (like, FACTS and NGH damping scheme) and DFIG controllers (in DFIG based wind farms). The solutions using FACTS devices and DFIG converters are more effective, however using FACTS devices only for SSR mitigation is not economically justifiable.
- The control loops of the rotor-side converter in DIFG have a negative impact on SSR modes, while the grid side converter has a major impact on improving the damping of SSR modes. Design of auxiliary damping controller through the voltage

modulation or DC link voltage in control loops of the network adapter is one of the most effective solutions for SSR damping.

- Rotor-speed, line current, and capacitor voltage are the main control signals for SSR mitigation. It has been shown that the capacitor voltage is an effective signal to increase the damping for both SSR and super-synchronous modes. The line current and rotor speed cannot simultaneously improve these modes and require sophisticated and complex controllers. Recent researches have also proposed the rotor speed signal for SSR mitigation using FACTS controllers.

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